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A DEVICE AND METHODOLOGY FOR MEASURING REPETITIVE LIFTING $\dot{V}O_2max$

U S ARMY RESEARCH INSTITUTE OF ENVIRONMENTAL MEDICINE

Natick, Massachusetts

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A repetitive lifting device capable of reliably operating under heavy loads for prolonged periods was designed to study manual material handling problems unique to the Army. The device consists of a pneumatically driven platform which can lift or lower loads up to 100 kg, from 0 to 200 cm above floor level. The device was utilized to develop a multi-stage repetitive lifting maximal oxygen uptake procedure and is suitable to be used for a wide variety of lifting and lowering tasks. There have been no device related injuries and little down time due to mechanical failure during more than 560 hours operating time. The mean repetitive lifting maximal oxygen uptake was 3.2 0($l \cdot min^{-1}$), which is similar to previous studies. The repetitive lifting device and VO_2max test should prove useful in the study of high intensity repetitive lifting problems.

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HUMAN RESEARCH

Human subjects participated in these studies after giving their free and informed voluntary consent. Investigators adhered to AR 70-25 and USAMRDC Regulation 70-25 on Use of Volunteers in Research.

A device and methodology for measuring repetitive lifting $\dot{V}O_2max$

No. T31/87

Marilyn A. Sharp, Joseph M. McGrath, Everett Harman,

Joseph J. Knapik, William A. Sawyer and James A. Vogel

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US Army Research Institute of Environmental Medicine

Natick, MA 01760-5007

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Abstract

A repetitive lifting device capable of reliably operating under heavy loads for prolonged periods was designed to study manual material handling problems unique to the Army. The device consists of a pneumatically driven platform which can lift or lower loads up to 100 kg, from 0 to 200 cm above floor level. The device was utilized to develop a multi-stage repetitive lifting maximal oxygen uptake procedure and is suitable to be used for a wide variety of lifting and lowering tasks. There have been no device related injuries and little down time due to mechanical failure during more than 560 hours operating time. The mean repetitive lifting maximal oxygen uptake was 3.2 0($l \cdot min^{-1}$), which is similar to previous studies. The repetitive lifting device and $\dot{V}O_2max$ test should prove useful in the study of high intensity repetitive lifting problems.

Introduction

A task analysis of the Army's 352 enlisted military occupational specialties revealed that more than 90% of the physically demanding tasks required heavy lifting(11). In the past, the majority of lifting research performed by the Exercise Physiology Division of USARIEM involved a one repetition maximal lift. As many Army tasks are repetitive in nature, carrying patients, loading ammunition or supplies for example, the study of physiological responses to repetitive lifting was deemed necessary. Most industrial materials handling research has centered on long term worker productivity and decreased injury rates. What has not been examined in industrial research is high intensity, maximal effort repetitive lifting. Industry has far more flexibility than the military in its ability to control the working environment, adjust lifting mass and rates, and use ergometric aids to make a task easier. Military materials handling research, while concerned with soldier safety, must primarily focus on determining the physiological effects of and limitations to high intensity repetitive lifting. Military lifting is often more demanding than industrial lifting in both mass lifted and rate of lifting. The success of a military mission, as well as the survival of the individual soldier, may depend upon a soldier's ability to move large volumes of supplies and ammunition quickly. For example, a self propelled howitzer crew must be able to lift, carry and load up to 600 ninety pound shells over a 24 hour period. Each 90 lb shell is lifted a minimum of 2-3 times in the loading and firing process.

A device capable of reliably operating under heavy loads for prolonged periods was fabricated in order to study the physiological responses to this type of high intensity repetitive lifting exercise. The first objective in this new research area was to develop a repetitive lifting maximal oxygen uptake procedure ($\dot{V}O_2$max test) to provide a means of describing lifting intensity among individuals as a percentage of their repetitive lifting $\dot{V}O_2$max. The purpose of this technical report is to describe the repetitive lifting device and the repetitive lifting $\dot{V}O_2$max testing procedures.

Instrumentation

The repetitive lifting device was modelled after a device reported by Snook and Irvine (9) and is similar in function to an elevator. When a load is lifted onto the raised shelf, the device lowers the load. When the load is pulled off, the lowered shelf rises and the lifting process can be repeated, as seen in Figure 1. The device can also raise a load that has been lowered onto it when in the "raise load" operating mode. The vertically moving shelf is driven up and down by a large bore, dual-acting, pneumatic cable cylinder. The shelf is guided by two vertical 304 cm chrome-steel linear bearing shafts, as illustrated in Figure 2. The shelf has an adjustable and controlled rate of lift as well as descent, and can raise or lower loads up to 100 kg. The shelf movement range can be set anywhere from 0 to 200 cm above the floor using the upper and lower limit stops illustrated in Figure 3. The limit stops are

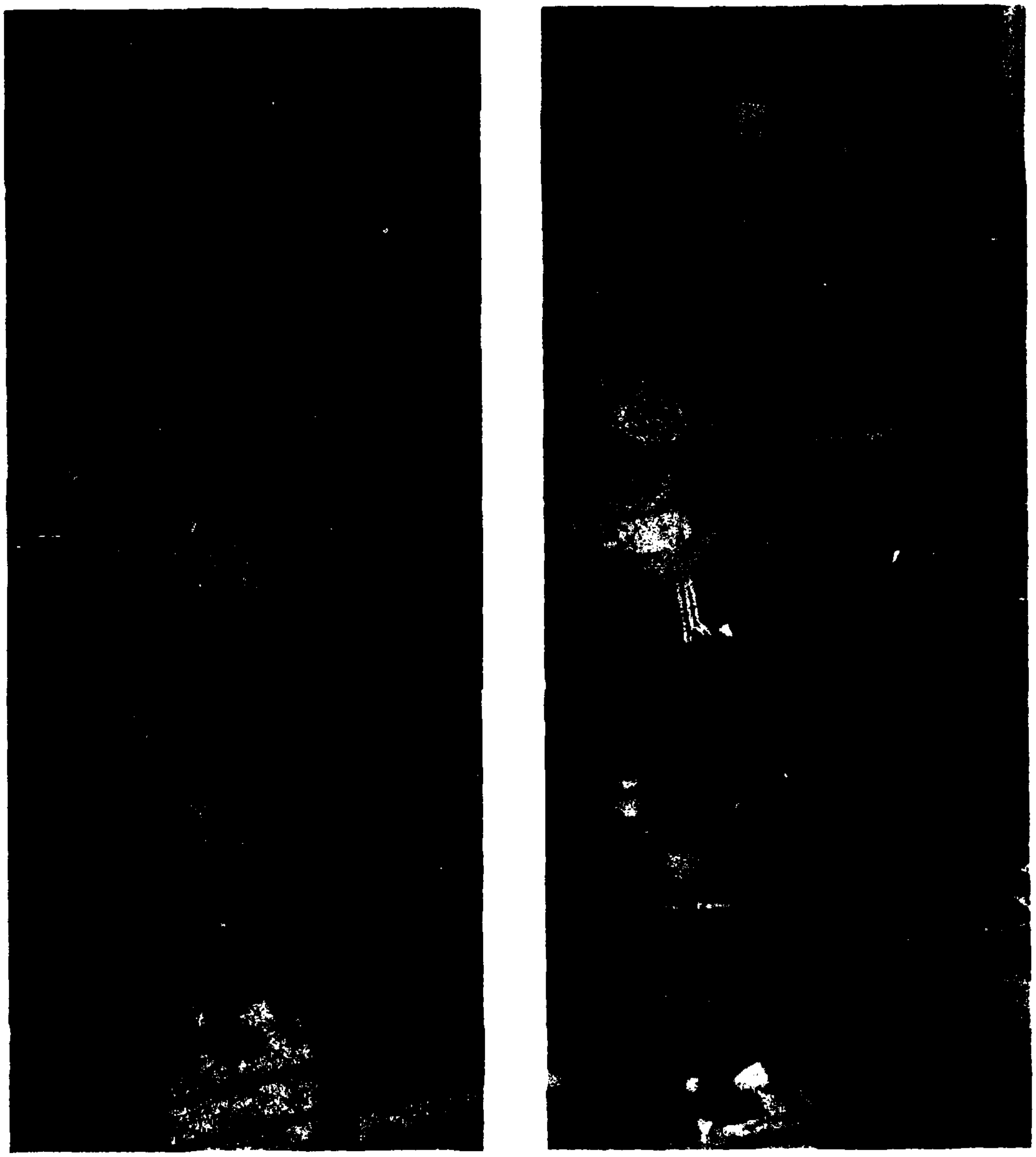
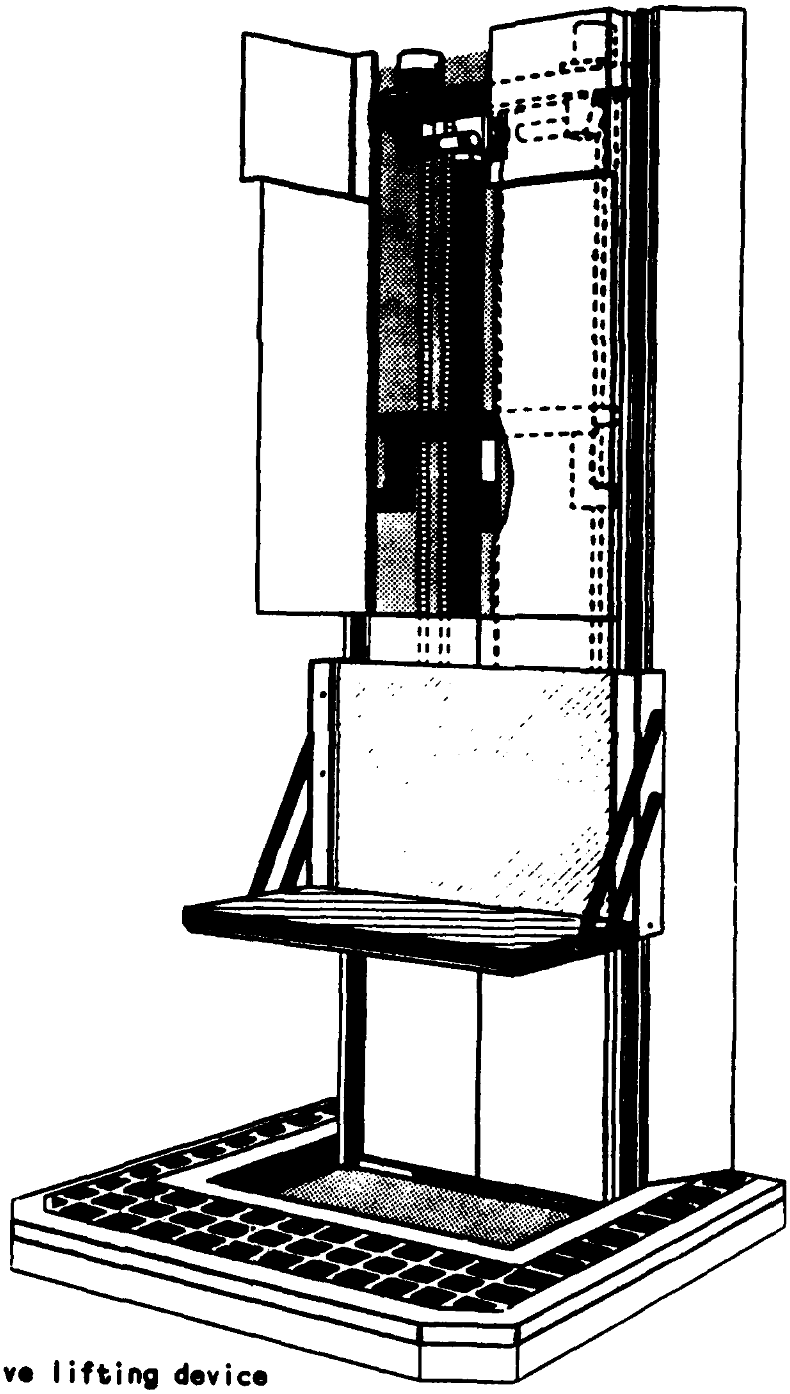
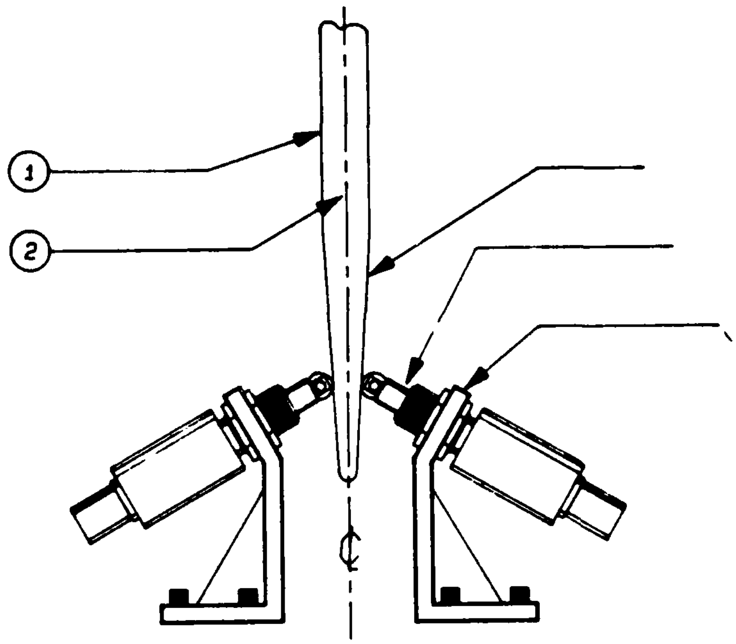


Figure 1. a. Beginning of lift. b. Completion of lift.



Repetitive lifting device

Figure 2.



1. Double ended pawl attached to carriage
2. Steel, 3/8"thk
3. Taper, 2 1/2° either side of center (5° total) with case hardened surface treatment
4. Plunger switch, spring loaded, with bearing end (diametrically opposed switches provide electrical redundancy)
5. Steel angle, 1/4"thk, with gussets

Figure 3. Limit stop assembly.

individually adjustable, and can be changed during lifting operation, using momentary rotary switches on the operator control panel. The limit stops are supported by 320 cm (10') long, 1.9 cm (3/4") Acme threaded drive screws driven by AC gearhead motors. Pneumatic caliper brakes assure shelf stability with no slippage during loading. The gearhead motors and caliper brakes are illustrated in Figure 4.

The device is user paced, responding to the subject's lifting rate. When a metal box is placed on or removed from the shelf, a field proximity sensor embedded 2mm below the ABS plastic shelf surface detects the presence of the box and activates shelf movement. The sensor, shown in Figure 5, is not visible on the shelf surface and is sensitive to non-ferromagnetic as well as ferrous materials. While the maximum possible rate of lifting is limited by the distance the platform moves and the skill of the subject, skilled lifters moving from floor level to shoulder height have achieved rates exceeding 20 lifts/min.

Figure 4. Gearhead motor and caliper brake assembly.

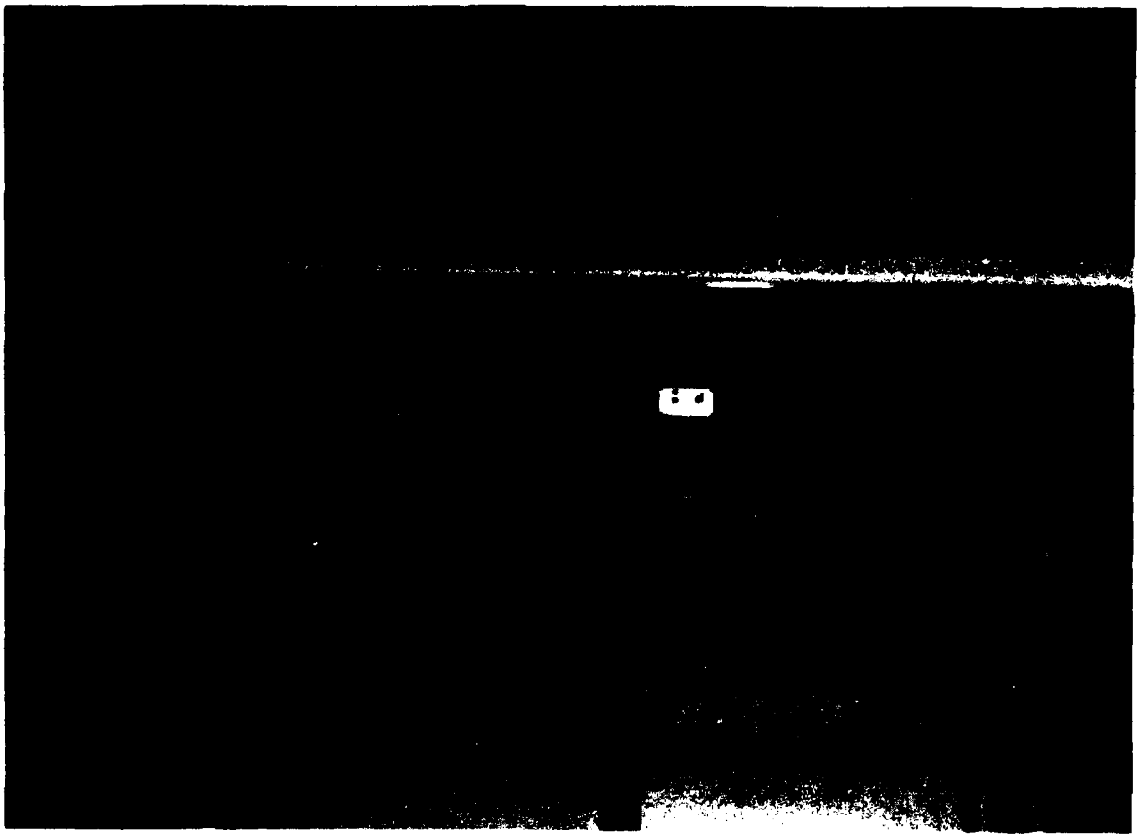


Figure 5. Repetitive lifting device shelf and field proximity sensor.

The repetitive lifting device is located in a finished laboratory area. In order for the shelf to reach zero elevation (flush with the floor) a platform was constructed of a 12" on-center grid of 1-1/2" wide spruce sheathed on top with 2 sheets (double thickness) of lumbercore plywood. As seen in the cutaway drawing in Figure 6, a sheet of 0.025" tempered aluminum was contact cemented to the top sheet of plywood. 3M Safety-Walk tiles were then applied to the aluminum to provide a non-skid surface. The edge of the platform was treated with a safety stripe to avoid a trip hazard. The platform is anchored to the concrete floor with 1/4" threaded drive pins and may be removed and stored vertically when not scheduled for use.

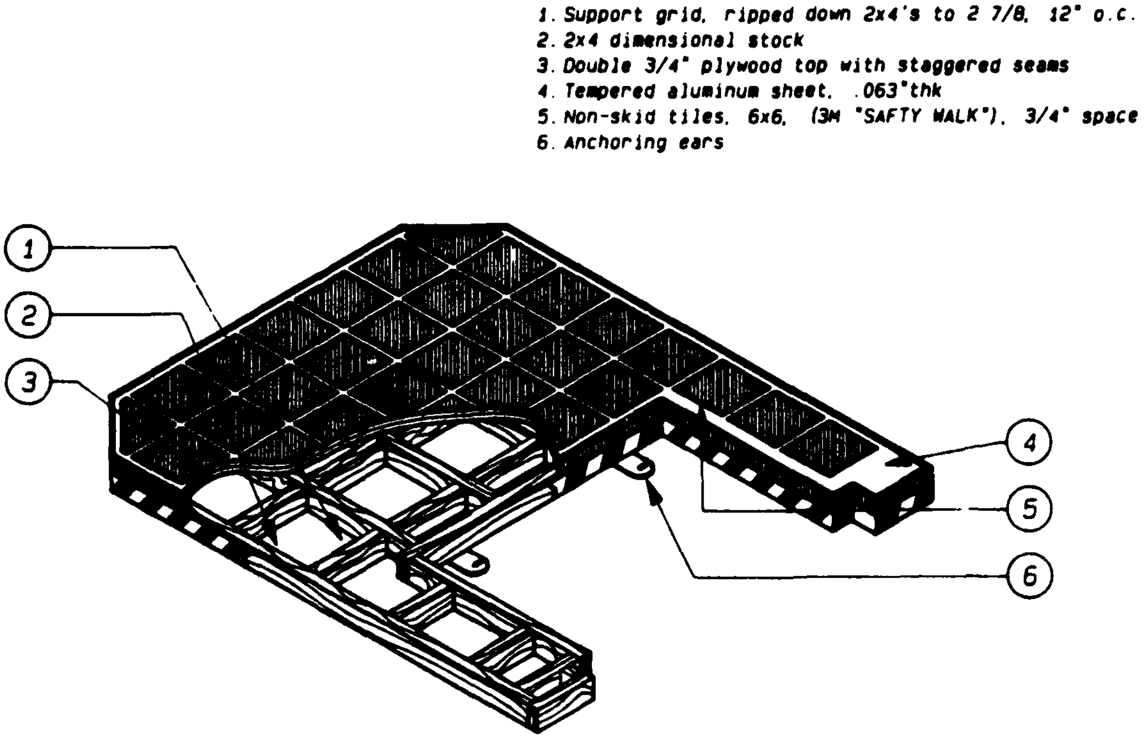


Figure 6. Cutaway drawing of repetitive lifting device platform.

The operator control panel shown in Figure 7 contains a directional (Task) switch to set the mode to either lifting or lowering. The upper and lower limit controls allow the operator to set the shelf movement to begin and end at any height between 0 and 200 cm. When anatomical lifting distances such as knuckle to shoulder height are used, lifting distances can be easily recorded from a vertical scale on the device doors and replicated from test to test. The device has automatic

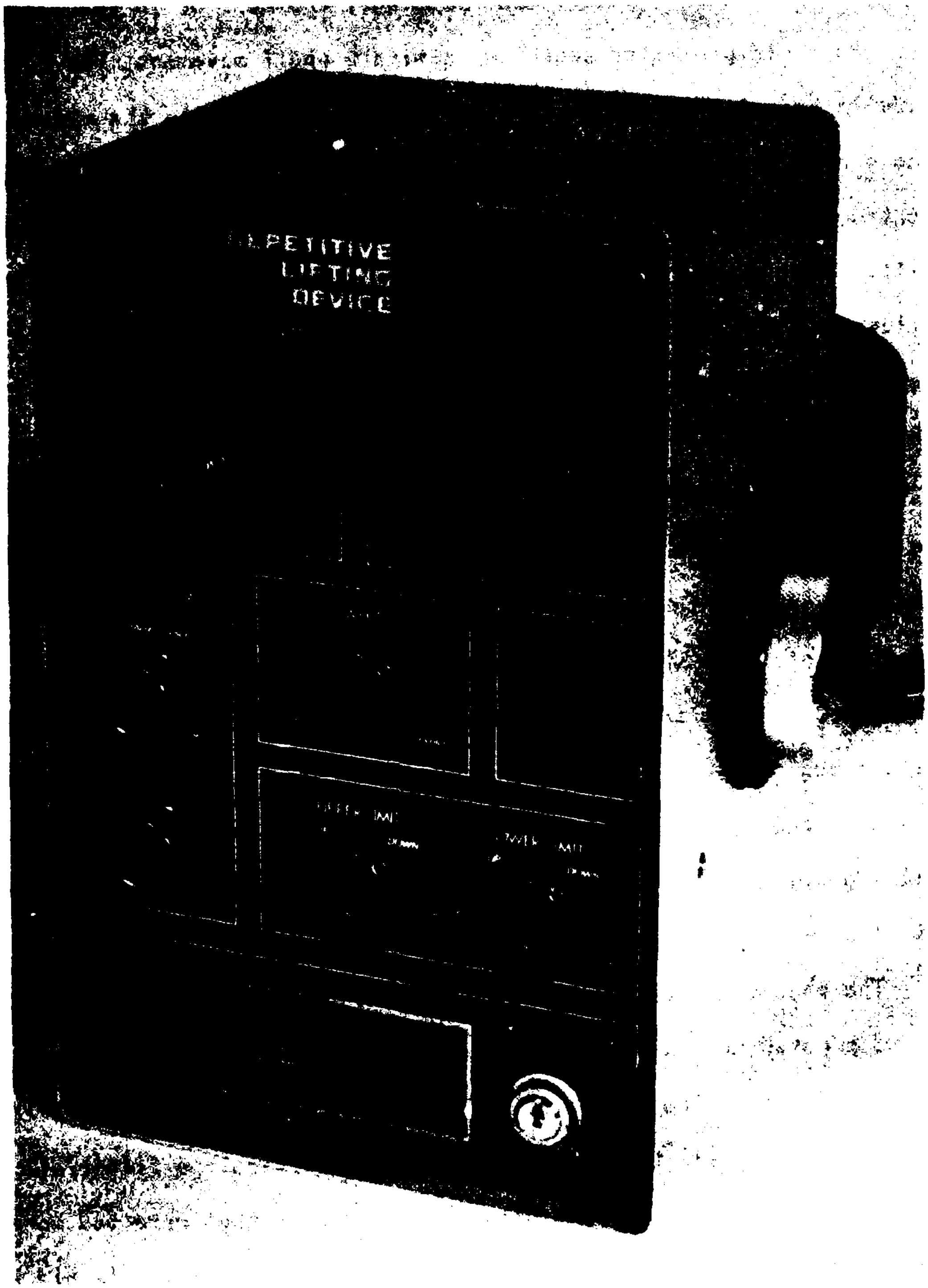


Figure 7. Operator control box.

(normal) and manual (pause) mode settings, and must be in automatic mode for the field proximity sensor to activate shelf movement. The automatic mode is used for all repetitive lifting trials. When in the manual mode, the shelf only moves when the manual "raise shelf", "lower shelf" controls are pressed. This mode is used to measure a single maximal lift. The panel also contains an emergency "safety" control which allows the operator to disable the device. A digital exercise timer (elapsed exercise time) and lift cycle counter (repetitions) are initialized at the beginning of the exercise period and allow for accurate assessment of lifting duration and rate. The exercise timer can be temporarily paused to allow for breaks in lifting. The timer is set and the lift counter reset with the device in pause mode. The pause - resume control is then used to activate the automatic mode and start the exercise timer at the same instant the subject starts lifting. When the lifter begins to pull the box from the shelf, the resume control is pressed, and the counter and timer record progress. The repetitive lifting device requires 117 VAC line voltage single phase and 861.8 kPa at .113 m^3/min (125 psi at 4 ft^3/min) compressed air.

The pneumatic controls (Figure 8) are contained in an oil/airtight, sound proofed enclosure, and wall mounted adjacent to the repetitive lifting device. They consist of a 2-way solenoid valve enabling the house air to enter the system, through a particulate filter/oil trap, oil fogger and pressure regulator. The air is then directed to either end of the cable cylinder via two 3/8" lines by a 4-way solenoid valve, each through an adjustable flow control/check valve. To reduce noise,

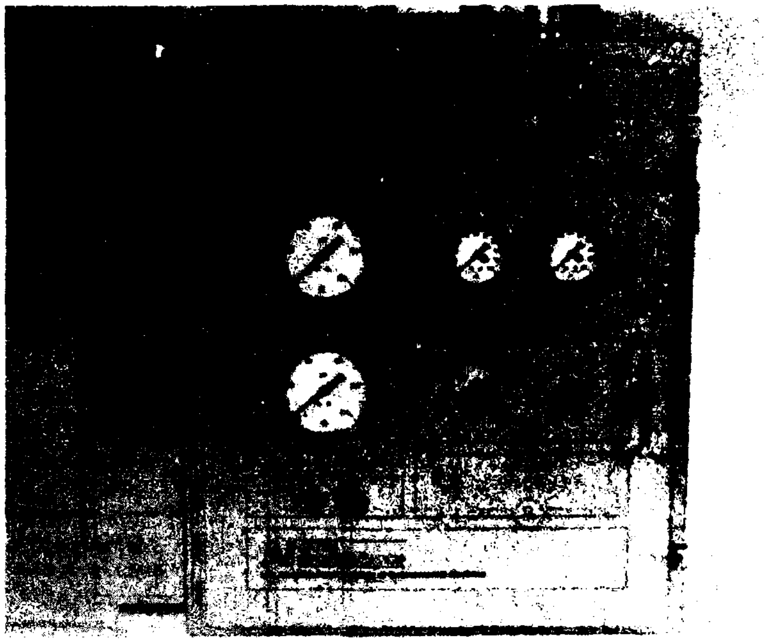
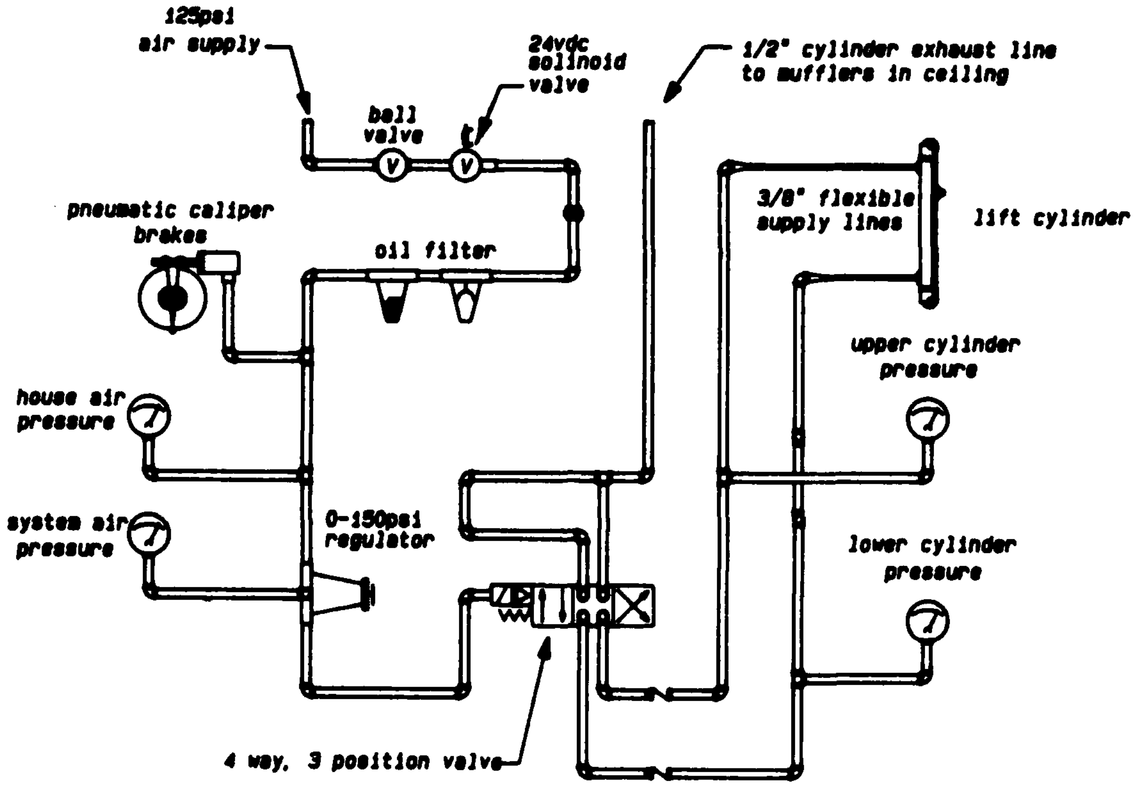


Figure 8. Pneumatic control box


125psi
air supply
24vdc
solinoid
valve
1/2" cylinder exhaust line
to mufflers in ceiling
ball
valve
pneumatic caliper
brakes
oil filter
3/8" flexible
supply lines
lift cylinder
upper cylinder
pressure
house air
pressure
system air
pressure
0-150psi
regulator
lower cylinder
pressure
4 way, 3 position valve

the exhaust ports of the 4-way solenoid valve are teed together, plumbed to the outside and terminate in a pair of low restriction mufflers, and the pneumatic components are mounted in a sound proofed box. Four gauges mounted on the front panel of the pneumatic control box indicate house and system air pressures, and upper and lower cable cylinder pressures. Figure 9 illustrates system air flow.

The electrical control box is mounted to the side of the pneumatic control box next to the low voltage power supply. It contains timing circuitry providing up/down shelf movement delays, limit switch override controls, an operator control panel disable switch and an elapsed time clock for maintenance purposes. A timeout clock is also included to shut down the device after 3 continuous hours of inactivity. An electrical control schematic is provided in Figure 10. All controls in the RL device are low voltage: +24VDC, +15VDC or +5VDC. Table 1 provides specifications for the device.

A teflon coated aluminum box was fabricated to be used with the device as shown in Figure 11. Box dimensions were 46.5 x 31 x 23 cm with handles attached 15 cm above the box bottom. Iron shot is used as a loading material which allows for fine adjustment in box mass. A removable partial containment grid placed inside the box stabilizes the iron shot. A semi-circle opening cut in the top of the grid allows easy removal of iron shot. The empty box and grid weigh 7.8 kg, and up to 100 kg of iron shot is available for loading. Box mass is measured by placing the box on an Electroscale weightmeter 551 platform scale, accurate to 0.1 kg.

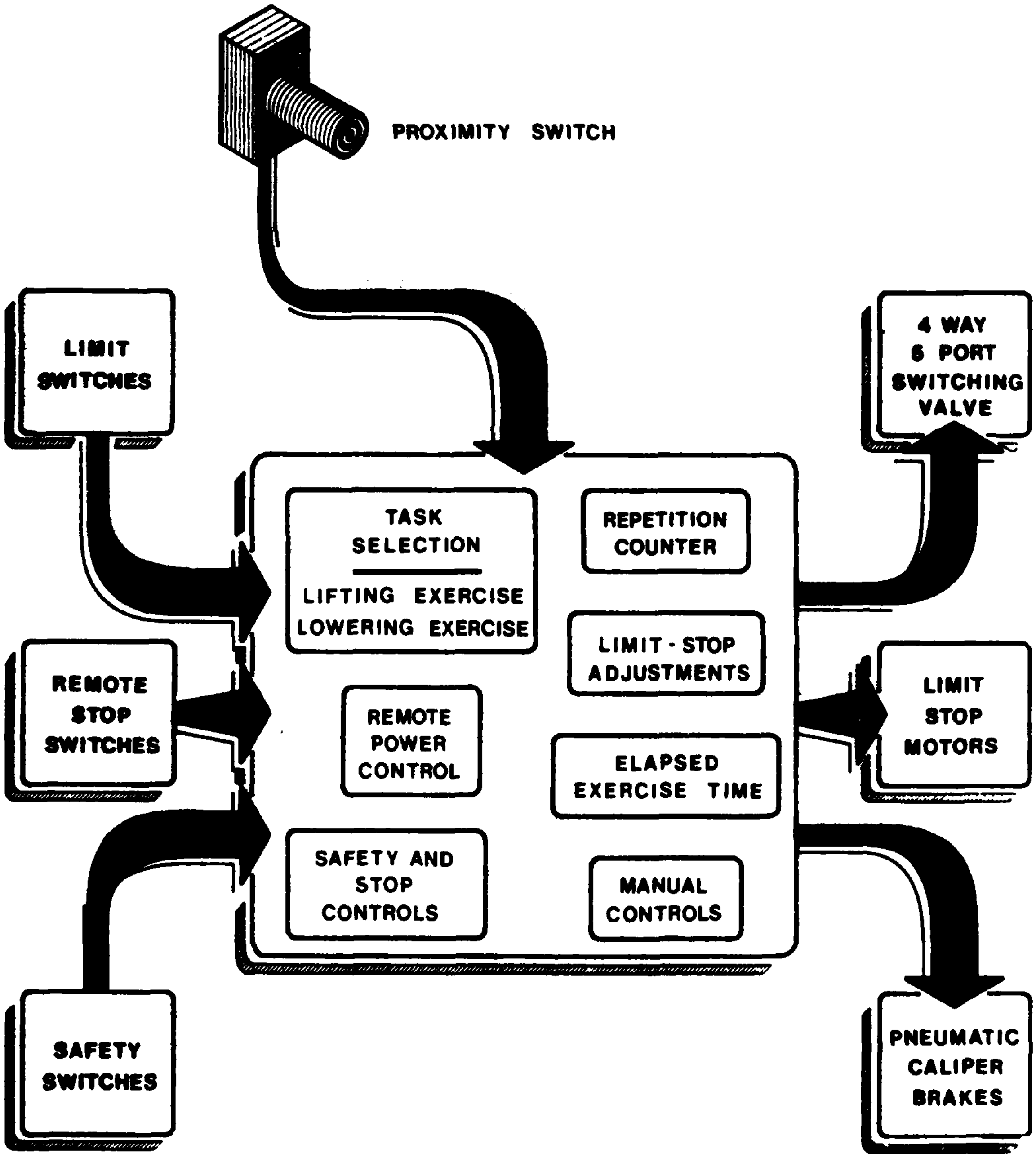
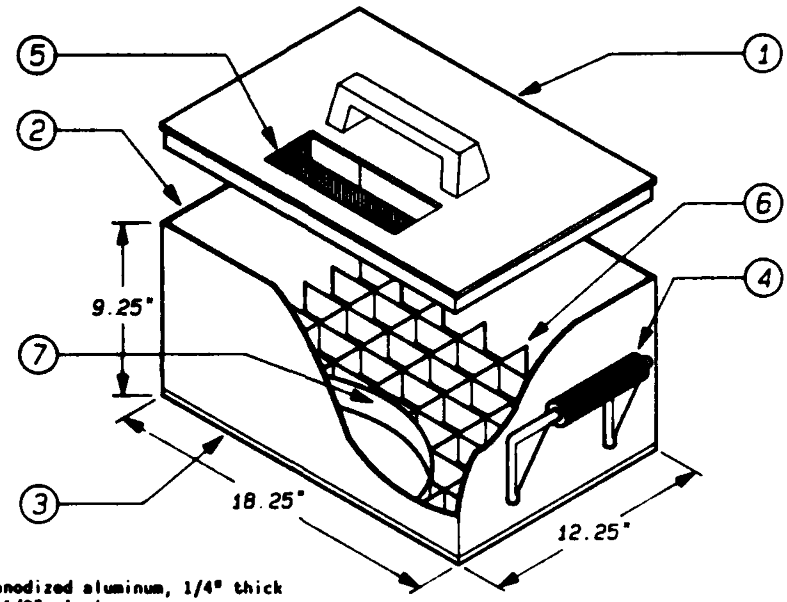


Figure 10. Electrical control sche

Table 1. Repetitive lifting device specifications

Dimensions:	
Height	320 cm (126")
Width	frame, 94 cm (37") w/ skirts, 122 cm (48")
Depth (out from wall)	frame, 23 cm (9") w/ shelf, 74 cm (29")
Weight (unloaded)	409 kg (900 lbs)
Platform:	
Dimensions	183 x 152 x 11 cm
Surface	non-skid (3M Safety-Walk)
Compressed Air Source:	
Pressure	861.8 KPA (125 psi)
Volume	.113 m^3/min
Electrical Requirements:	117VAC, 1ϕ, 20A branch service
Shelf Velocity (raise/lower, empty)	1.3 m/sec (varies w/pressure)
Shelf Loading Capacity:	100 kg (220 lbs)
Shelf Surface:	3 cm A.B.S. board
Cylinder Thrust:	280 kg (615 lbs)
Mounting:	
Bolted to 6" concrete block wall at 8 locations.	
Vibration isolation at wall and floor.	
Prime mover: dual acting cable cylinder	
Bore:	6.35 cm (2 1/2")
Stroke:	260 cm (102")
Creep (movement of limits during operation)	0
Response/Delay time:	
After load is in place	0-5 seconds
After load is removed	0-5 seconds

Major Components - Manufacturer
- Cable cylinder - Tol-O-Matic (custom built)
- Proximity switch - Eldec
- Screw drive motor - Bodine
- Brake cylinders - Bimba
- Acme drive screws - Ray Industries (custom built)
- Cycle counter - Veeder/Root
- Exercise timer - Kessler-Ellis (custom built)
- Shock absorbers - Ace Industries
- Four-way valve - AAA Products



1. Friction fit cover, anodized aluminum, 1/4" thick
2. Sides constructed of 1/8" aluminum
3. Box bottom, 3/8" aluminum (milled flat after welding)
4. Knurled grips, both ends
5. Blind hole for adding ballast during exercise
6. Removeable containment grid
7. Cut-out area for scoop

Figure 11. Repetitive lifting box and partial containment grid.

Extensive measures were taken to ensure the safety of human test subjects. All potential "pinch points" smaller than 6 mm were minimized, sharp corners were softened and any exposed steel in the operating area of the test subject was sheathed with plastic. A continuous Tapeswitch was placed on the bottom edges of the shelf to stop shelf descent if a body part or other object contacts it. Shelf movement may be delayed between 0 and 5 sec following activation of the proximity sensor, using the manually set delay-up and delay-down controls. This delay allows an inexperienced lifter to pull the box off the shelf slowly, without the shelf rising before the box is completely removed. Shortening the delay allows the experienced lifter to lift at a faster rate. Kill switches were placed behind the front panels to disable the device should the subject fall forward while lifting. To prevent a safety problem due to switch failure, electrical redundancy was used on all safety and limit switches. A remotely located stop switch was placed opposite the control panel for emergency use by testing personnel.

Repetitive Lifting Maximal Oxygen Uptake Procedures

The repetitive lifting device has been used to develop a repetitive lifting maximal oxygen uptake procedure. This is a measure of the maximum rate at which one can utilize oxygen during lifting exercise. Eighteen male soldiers were recruited to participate in this study. They were briefed, medically screened and gave their informed consent to participate. The sum of four skinfolds (biceps, triceps, suprailiac and subscapular) was used to estimate body fat (2).

The lifting height used for the $\dot{V}O_2max$ test was 132 cm (approximately chest height for most males), which is the bed height of a standard Army 2-1/2 ton truck. The test began with a three minute warm up followed by three to five additional 2.5 to 3 minute lifting bouts of increasing intensity, each separated from the previous intensity by a 10 minute rest period. The initial box mass lifted was 15.2 kg, and was increased by 2 to 4.5 kg with each additional exercise bout. This initial box weight was used because the 7.8 kg lifting box described earlier was unavailable at the time data collection began, and a metal box weighing 15.2 kg was utilized. Subjects were instructed to lift at a rate of 15 lifts•min^{-1} and maintain this pace throughout each exercise bout using a freestyle lifting technique. The lifting rate was set by an electronic metronome, and subjects were observed and coached to maintain this pace. Extensive pilot testing found this to be the fastest rate all trained subjects could maintain while lifting to 132 cm. Slower rates with greater box masses tended to produce a lower repetitive lifting $\dot{V}O_2max$, probably due to upper body fatigue. Since lifting incorporates work in moving the body as well as a loaded box, a faster lifting rate allows the subject to achieve a higher gross power output while only lifting a moderate box mass (5). Several subjects assumed a pace slightly faster than 15 lifts/min, and all subjects were encouraged to lift as rapidly as possible during the maximum intensity load.

$\dot{V}O_2max$ was defined as a plateau in $\dot{V}O_2$ (<0.15 l•min^{-1} increase in $\dot{V}O_2$) with an increase in box mass of 2 kg. An attempt was made to reach a plateau on all tests, but during attempted maximal loads subjects were often not able to perform long enough to obtain adequate gas samples. A plateau was obtained on 7 of 18 repetitive lifting $\dot{V}O_2max$ tests. Even when true plateaus could not be reached, peak oxygen uptake indicates the maximal rate that subjects could reach, therefore all tests will be referred to as maximal oxygen uptake ($\dot{V}O_2max$).

Figure 12 shows a test subject set up for maximal oxygen uptake measurement. Expired gases were collected through a low resistance two way Daniels valve into vinyl Douglas bags during the last minute of each

Figure 12. Configuration of Daniels valve.

exercise level. The valve was secured to an adjustable plastic headpiece with elastic rope. Tubing was run into and out of the valve, back over the shoulders and tied together behind the back. The expired air tube was wound through the loop of a cloth belt. An optional leather weightlifting belt was provided, which could be worn under the cloth belt. Several subjects chose to wear the leather weight belt without the cloth belt. In those cases, the plastic tubing was secured to the back of the leather belt with tape. The mouthpiece and noseclip were in place throughout the lifting exercise. Two 30 second samples were collected during the last minute of lifting exercise at each intensity. Expired gas samples were analyzed for gas fractions with Beckman LB-2 CO_2 and Applied Electrochemistry S-3A O_2 gas analyzers. Gas volumes were measured with a Collins chain-compensated Tissot spirometer. Heart rate was continuously monitored with an oscilloscope and recorded on an electrocardiograph during each $\dot{V}O_2max$ test. Disposable electrodes were placed in a CM5 configuration to avoid excess EMG and movement artifact during upper body exercise. The heart rate reported was recorded during the last 30 seconds of exercise.

Each subject practiced lifting for a minimum of two weeks, 3 sessions per week to allow for familiarization with the apparatus and technique. The practice sessions consisted of an assortment of lifting tasks, from 10 minute determinations of maximal acceptable lift at 8 lifts/min to 3 minute exercise bouts at 15 $lifts \cdot min^{-1}$. Box mass was adjusted upward as the subjects became more skilled at lifting. It is not clear at this time the number of practice sessions needed to ensure a repeatable level of lifting skill, but this will be the subject of future investigations. Early pilot work indicates that there are improvements in lifting efficiency after only one practice session. Seven subjects agreed to repeat the repetitive lifting $\dot{V}O_2max$ test to assess reliability.

The power required for the box lift was calculated using the following equation, which takes into account work in raising both the box and the lifter's body.

$$P = F(W_B T_B + W_L T_L)/60.0$$

where;

- P = power (watts)
- F = lift frequency (lifts/minute)
- W_B = box mass (newtons)
- T_B = vertical box travel (meters)
- W_L = lifter's body weight (newtons)
- T_L = vertical travel of the lifter's center of mass (meters)

Vertical box travel was taken as the vertical distance between the floor and shelf upon which the box was placed. Vertical travel of a subject's center of mass during lifting was calculated from films taken with a Locam camera (Redlake Corp, Morgan Hill, CA) at 60 frames per second. The films were projected onto the back of a translucent glass screen, and the frames where the lifter's body was highest and lowest during a lift were located. Graph paper tracings were made in which dots were drawn over the wrist, elbow, shoulder, hip, knee and ankle joints, and lines drawn between the dots to represent the major body segments. Using an anthropometric table, the center of mass of each body segment was located as a proportion of the distance between the segment ends, and marked on the tracings. The whole body vertical center of mass was calculated using the following equation (12):

$$y_{cm} = \sum_{i=1}^{n} f_i y_i$$

where

y_{cm} = vertical coordinate of the lifter's center of mass

y_i = vertical coordinate of the i^{th} body segment

f_i = i^{th} segment's fraction of total body mass (from table)

n = number of segments in body model

The vertical travel of the lifter's center of mass was taken as the difference between the highest and lowest vertical coordinates of his center of mass during the lift. A multiplying factor derived from the tracing and measurement of an object of known size in the camera's field of view was used to obtain the vertical distance in meters of the high and low point of the body center of mass from the corresponding graph coordinates.

One repetition maximal (1RM) lift was determined using two different methods. With the first, the subject repeatedly lifted the handles of a weight stack machine from a starting height of 20 cm to a final height of 152 cm (4). The mass lifted was increased by 4.5 kg (one weight plate) with each lift, until the subject failed at a lifting attempt. The subject was required to use a bent knee, straight back lifting technique. The mass range of the weight stack was 20 - 91 kg. The last successful load lifted prior to failure was accepted as the maximal machine lift. The incremental lift device and test procedures are described in more detail elsewhere (10).

A second determination of 1RM lift was made using the repetitive lifting device with the shelf locked at 132cm and a box similar to that used during the repetitive lifting $\dot{V}O_2$max test. Following a warm up, mass was added to the box with each successful lift to 132 cm in increments between 1 and 11 kg. The weight increments were based on the test administrator's and subject's subjective evaluation of the difficulty encountered in lifting the previous box mass. As box mass reached higher levels, the increments were smaller. Approximately one minute rest was allowed between lifts, and an attempt was made to reach the subjects' maximum within 5 to 7 lifts. The last successful weight lifted prior to subject failure was accepted as the maximal box lift. The box was lowered by the device after each successful lift. Experienced test administrators stood on either side of the subject, and assisted in lowering the box during the final (unsuccessful) lift attempt.

The economy of exercise (1), defined as power output divided by oxygen uptake ($W/l \cdot min^{-1}$), was determined for each exercise bout performed on the repetitive lifting device. Absolute power output varied considerably between subjects, as did the number of submaximal lifting bouts. In order to examine exercise economy across intensities, the data were grouped into three relative intensity categories. The intensity levels were 60-74%, 75-90% and >91% power output at $\dot{V}O_2$max.

Pearson's correlation coefficients were used to examine relationships between descriptive measures and repetitive lifting $\dot{V}O_2$max test responses.

Results

Descriptive statistics for age, height, weight, body composition and maximal lifts of the subjects are listed in Table 2. Physiological data from the repetitive lifting $\dot{V}O_2max$ test are shown in Table 3. An intraclass reliability coefficient of 0.91 was determined using the results of seven subjects who performed the repetitive lifting $\dot{V}O_2max$ test twice. No significant difference was found between trials in $\dot{V}O_2max$, in any of the other physiological variables, nor in the box mass at repetitive lifting $\dot{V}O_2max$. The subjects lifted an average of 41% ± 6% of their 1RM box lift during the final exercise bout of the repetitive lifting $\dot{V}O_2max$ test.

Table 2. Subject sample descriptive data (n=18)

	Age (years)	Height (cm)	Body Mass (kg)	Body Fat (%)	Fat Free Mass (kg)	1RM Machine Lift (kg)	1RM Box Lift (kg)
Mean	23.9	177.7	75.9	15.1	64.3	68.8	64.3
SD	3.7	8.9	8.8	4.7	7.0	11.3	11.8

The repetitive lifting power output vs $\dot{V}O_2$ relationship was linear for most individuals, with a median correlation coefficient of 0.98, however, there was a large variation in slope from subject-to-subject. Economy of lifting at each intensity level is listed in Table 4. There was no significant change in economy of repetitive lifting across exercise intensity levels.

Table 3. Physiological responses to repetitive lifting $\dot{V}O_2max$. (n=18)

	Mean ± SD	Range
$\dot{V}O_2max$ ($l \cdot min^{-1}$)	3.20 ± 0.42	(2.49-3.99)
V_E BTPS ($l \cdot min^{-1}$)	109.9 ± 18.3	(71-146)
Heart Rate ($beats \cdot min^{-1}$)	181 ± 8.4	(168-198)
$\dot{V}E/\dot{V}O_2$	34.5 ± 4.5	(26.3-44.5)
RQ	1.02 ± 0.08	(0.86-1.17)

Table 4. Economy ($W/l \cdot min^{-1}$) of repetitive lifting exercise (Mean ± SD,(n))

Percent peak power output		
60-74%	75-90%	> 90%
59.0 ± 7.0 (9)	58.2 ± 9.3 (18)	60.7 ± 7.9 (30)

Table 5 lists correlations between variables measured during the repetitive lifting $\dot{V}O_2max$ test and several anthropometric and strength measures. Body mass, fat free mass and 1RM machine lift, three variables usually associated with muscle strength, were significantly correlated

Table 5. Correlation between repetitive lifting $\dot{V}O_2max$ test variables and selected anthropometric and maximal lift variables. (n=18)

	Height	Body Mass	Percent Body Fat	Fat Free Mass	Machine Lift[1]	Box Lift[1]
$\dot{V}O_2max$ ($l \cdot min^{-1}$)	.473	.527*	-.156	.622**	.619**	.276
Heart Rate	-.266	-.168	-.291	-.036	.159	-.204
$\dot{V}_E$ ($l \cdot min^{-1}$)	.249	.416	-.275	.557*	.718**	.012
$\dot{V}_E/\dot{V}O_2$	-.228	-.052	-.214	.041	.271	-.360
Box Mass	.271	.328	.057	.318	.429	.540*
Power Output	.482*	.333	-.553*	.622**	.596*	.411
Work	.445	.284	-.348	.469	.388	.205

1 n=17
* $p<.05$
** $p<.01$

with absolute repetitive lifting $\dot{V}O_2max$. Power output at repetitive lifting $\dot{V}O_2max$ was significantly correlated with height, percent body fat (negatively), fat free mass and 1RM machine lift. While peak power output was most highly correlated with fat free mass, persons with more fat free mass did not tend to lift a heavier box mass during maximal repetitive lifting exercise. 1RM machine lift significantly correlated with repetitive lifting $\dot{V}O_2max$ (r=0.619), but 1RM box lift did not.

1RM box lift was significantly correlated with the final box mass lifted during repetitive lifting $\dot{V}O_2max$ test, while the 1RM machine lift was not.

Discussion

The repetitive lifting device can be used for a variety of lifting tasks and training. Lifting tests can be as short as a single maximal lift and as long as 100 hours in duration. The vertical lifting/lowering distance can be set anywhere from just above the floor through full arms length above the head. The loads lifted can be as great as 100 kg, and lifted or lowered at high lifting rates.

The repetitive lifting $\dot{V}O_2max$ test was demonstrated to be a reliable measure of aerobic capacity during lifting exercise. Most individual subjects show a nearly linear increase in $\dot{V}O_2$ with power output during repetitive lifting exercise. Several investigators have either reported or assumed a linear relationship between power output and $\dot{V}O_2$ for repetitive lifting exercise (3,4,8). This assumption has been shown to be accurate at exercise intensities below 50% $\dot{V}O_2max$ (4). When submaximal and maximal repetitive lifting power output vs $\dot{V}O_2max$ data were plotted with all subjects combined, as shown in Figure 13, the linear relationship was not as strong (r=.65), probably due to the variation in both slope and economy between subjects. For determining exercise intensity, it is therefore necessary to determine each individual's physiological response to repetitive lifting exercise,

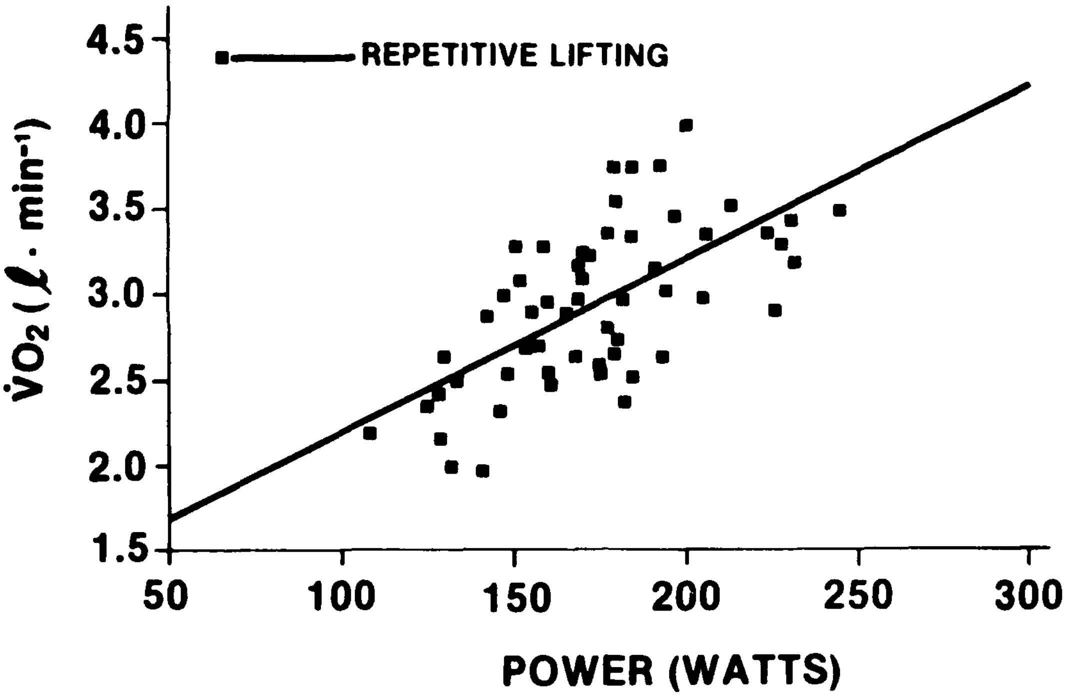


Figure 13. Plot of oxygen uptake against power output during reptitive lifting exercise.

rather than to assume a standard relationship for all subjects.

In a study of postage package handlers, Peacock (6) found anthropometric variables, particularly height, to be more important than absolute $\dot{V}O_2$ in successful task performance. In the present study, height was not significantly correlated with repetitive lifting $\dot{V}O_{2}max$, but was correlated ($p<.05$) with power output during repetitive lifting exercise. It seems logical that a taller person should be able to lift a heavier box mass to 132 cm because of better mechanical advantage. For a single lift this appears to be true, as height was significantly correlated with maximal box lift ($r=.63$). This was not the case for repetitive lifting, however, as height was not significantly correlated with final box mass lifted during the $\dot{V}O_2max$ test. The relationship between height and power output during repetitive lifting is probably due to the greater excursion of the center of mass of taller persons during the floor to 132 cm lifting task. A similar relationship seems to hold true for fat free mass and power output (r=.62). Fat free mass was not significantly correlated with the final box mass lifted, therefore, persons with more fat free mass achieved higher power outputs without lifting a heavier box mass. These findings lend support to the importance of including the work done to move the body center of mass in the calculation of power output during repetitive lifting exercise.

Table 6 compares the repetitive lifting $\dot{V}O_2max$ test data from the present experiment with that of Petrofsky and Lind (7) and Intaranont et al. (3). Due to greater vertical movement of the body's center of mass, the repetitive lifting $\dot{V}O_2max$ testing procedures used in this study were expected to yield a higher repetitive lifting $\dot{V}O_2max$ than those obtained previously (3,7). Power output in the present experiment was 15-30 watts greater than that of Petrofsky and Lind (7) without consideration of the work done to move the body, yet the repetitive lifting $\dot{V}O_2max$ obtained was only slightly higher (Δ=0.19 $l \cdot min^{-1}$). Based on submaximal repetitive lifting, Intaranont et al. (3) estimated repetitive lifting $\dot{V}O_2max$ to be 3.16 $l \cdot min^{-1}$ when lifting from floor to knuckle height and 2.86 $l \cdot min^{-1}$ when lifting from knuckle to shoulder height. Lifting from floor to knuckle height resulted in a higher

Table 6 Comparison of Repetitive lifting $\dot{V}O_2max$ test data from the present experiment with that of other experiments

	Petrofsky and Lind	Present Study	Intaranont et al.
Box Mass (kg)	36.36	26.3	27.2
Power (watts)[1]	70.6	93.3	NA
Lift Height (cm)	54	132	Floor to knuckle
Rate ($lift \cdot min^{-1}$)	20-24	15-20	9
$\dot{V}O_2max$ ($l \cdot min^{-1}$)	3.01 ± 0.36	3.20 ± 0.42	3.16[3]
Heart rate (bpm)	182	181	122

[1] Calculated without body mass.

[2] NA= not available.

[3] predicted $\dot{V}O_2max$ based on three submaximal loads all other parameters are the mean of the highest intensity reported.

$\dot{V}O_2max$ than that reported by Petrofsky and Lind (7) for lifting to a similar height, and almost equalled the repetitive lifting $\dot{V}O_2max$ of the floor to shoulder height lift in the present study. The floor to knuckle lifting was performed using a squat technique. This requires the lifter to do more work in moving his body than the stoop technique used by most of Petrofsky and Lind's (7) and the present experiment's subjects. Regardless of lifting technique, the difference in $\dot{V}O_2max$ between a lift from floor to knuckle height and floor to shoulder height is small. The majority of the energy requirement comes from the floor to knuckle phase of the lift, during which the body weight must also be lifted. It is during this phase that the momentum is built up that helps to carry the box through the above waist portion of the lift. The additional energy requirement for moving the arms appears to be small. This may explain why height and repetitive lifting $\dot{V}O_2max$ were not significantly correlated.

A limitation to the procedures described here is that the lifting intensity did not start at a low enough level. It is recommended that the initial lifting bout be performed with an empty box to provide adequate warmup for all test subjects. Starting with a 15.2 kg box resulted in a very high initial exercise intensity for some subjects.

Conclusions

The repetitive lifting device has demonstrated a capacity for very heavy loads and fast lifting rates. It can be used to examine a great variety of repetitive lifting and lowering tasks, or to determine 1RM lifting strength. The device facilitates the study of physiological responses to repetitive lifting exercise, and has been used to develop a reliable $\dot{V}O_2$ max testing procedure for repetitive lifting exercise. There have been no device related injuries, and little down time due to mechanical failure during approximately 560 hours operating time.

The repetitive lifting $\dot{V}O_2max$ test presented here is a reliable means of assessing aerobic capacity for repetitive lifting, which parallels standard ergometric methods and should prove useful as an occupational lifting research tool.

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Appendix

REPETITIVE LIFTING DEVICE

Preventative Maintenance Schedule

This schedule will list all lubrication points on the Lifting Device and the frequency of service. This information is directed mainly to maintenance personnel, however section II of this schedule pertains to areas that investigator/user personnel should pay attention to.

PART I - LUBRICATION

OIL (5wt Light Weight Motor Grade Oil)

1. Linear bushing bearings - 4 each located on the carriage at top right, top left, bottom right, and bottom left. NOTE: Bearings are not visible as they are protected by felts above and below each bearing. Each felt has a retaining cup over it. 10 drops of oil on each felt every 25 hours
2. Drive Screw Transmission - 2 roller chains and 4 sprockets located at the base of the device near the floor. Carriage must be elevated to access these points. 10 drops on each sprocket every 50 hours.
3. Sleeve Bearings (brass) - 8 each located at the top and bottom of each acme drive screw. Carriage must be elevated and doors opened to access bottom 4 points and lowered and top doors opened to acess top 4 points. 5 drops of oil at each point every 25 hours.
4. Limit Switches - 2 each located on each buffer unit right of center and one each on each buffer unit far left end. Follow access procedure shown in step 3 above. 3 drops at each point every 25 hours.
5. Limit Switch Cams - 2 points located on back of carriage. Access upper cam by lowering carriage midway, opening upper doors and put head into opening and look down. 5 drops of oil on each side every 25 hours. Access bottom cam by raising carriage above midpoint, open bottom doors inset head, look up. 5 drops of oil each side of cam every 25 hours.
6. Vee Guide Pulleys - 4 each located on 2 buffer units (8 total). Access these points by following procedure in step 3 above. 3 drops at each point every 50 hours.
7. Vee Guides - 2 each located inside device one on left and one right. Oil a clean cloth and wipe each guide from top to bottom once every 100 hours.
8. Pneumatic Fogging system - Located in control cabinet (blue) on wall to left of Lifting Device. Ensure that oil reservoir has at least 1" of pneumatic tool oil every 25 hours.

REPETITIVE LIFTING DEVICE

PM Schedule Part I (continued) Lubrication

9. Pneumatic Brakes - 2 each located inside at top of device. 2 drops on each hindge pin every 100 hours.

10. Carriage Supports - 6 points along horizontal shelf portion of carriage and 4 points along vertical portion of carriage, 5 on left and 5 on right. One drop of oil at each point once every 50 hours.

GREASE (Light weight lithium instrument grease)

1. Acme Threaded Drive Screws - 4 each inside, 2 on left and 2 on right. With a flux brush wipe grease into threads over entire length of screw and wipe off excess once every 100 hours. NOTE: Donot grease screw in area of pneumatic brakes.

PART II - INSPECTION

DAILY

1. Ensure that air pressure to cable cylinder is minimum necessary to accomplish required lift; excess air pressure put needless stresses on many system components.

2. User should be casually aware of anything that may be obviously wrong like loose bolts/screws/nuts etc. doors open ajar, unusual vibrations in device or noise being transmitted into building.

3. User should periodically test performance of all safety features and interlocks.

4. Note level of Pneumatic Oil in fogger located in control cabinet. Should be at least 1".

5. Any tell-tale air leaks should be reported to Instrumentation Lab.

6. If platform is removed during long inactive periods, ensure it is placed back in its origional location and securely bolted before operating device.

7. Wipe excess dirt or grit off table top periodically during operation.

8. Do not hang anything off cable connecting operator control box to blue logic package on wall.